Available online at www.sciencedirect.com
ScienceDirect
Fire Safety Journal 42 (2007) 482–488
FIRE SAFETY JOURNAL
www.elsevier.com/locate/firesaf

Critical factors governing the fire performance of high strength concrete systems

V.K.R. Kodur[a,*], L. Phan[b]

[a]Civil and Env. Eng., Michigan State University, East Lansing, MI, USA
[b]Building and Fire Research Laboratory, National Institute of Standards Technology, Gaithersburg, MD, USA

Received 17 August 2006; accepted 31 October 2006
Available online 21 June 2007

Abstract

High strength concrete (HSC), is being increasingly used in a number of building applications, where structural fire safety is one of the major design considerations. Many research studies clearly indicate that the fire performance of HSC is different from that of normal strength concrete (NSC) and that HSC may not exhibit same level of performance (as NSC) in fire. This paper discusses the material, structural and fire characteristics that influence the performance of HSC under fire conditions. Data from earlier experimental and numerical studies is used to illustrate the impact the concrete (material) mix design and structural detailing (design) has on fire performance of HSC systems. An understanding of various factors influencing fire performance will aid in developing appropriate solutions for mitigating spalling and enhancing fire resistance of HSC members.

Keywords: Fire resistance; High strength concrete; Governing factors; Reinforced concrete columns; Spalling

1. Introduction

In recent years, the construction industry has shown significant interest in the use of high strength concrete (HSC), in applications such as bridges, offshore structures, and high-rise buildings. This is due to significant economic, architectural, and structural advantages HSC can provide compared to conventional, normal strength concrete (NSC). One of the major uses of HSC in buildings is for structural framing consisting of beams and columns, which are the primary load-bearing components, and hence, the provision of appropriate fire safety measures is a main safety requirement in building design. With the increased use of HSC, concern has developed regarding the behaviour of such concrete's in fire. In particular, the occurrence of spalling at elevated temperatures, as observed in studies carried out in a number of laboratories, was a reason for this concern [1–6].

Building codes generally specify fire resistance requirements for structural members. In North America, concrete structures are to be designed in accordance with the ACI standard [7] in USA and the CSA standard [8] in Canada. The recent edition of the standards contains detailed specifications on the design of HSC structural members; however, there are no guidelines for the fire resistance design of HSC structural members either in CSA standard [8] or the ACI standards [7,9].

Generally, concrete structural members (mainly NSC) exhibit good performance under fire situations. However, results from a number of studies [1–6,10–12] have shown that there are well-defined differences between the properties of HSC and NSC at high temperatures. Further, concern has developed regarding the occurrence of explosive spalling when HSC is subjected to rapid heating, as in the case of a fire [4,5,11].

Tracing the fire response of HSC structural system requires the use of accurate numerical models that properly account for material characteristics (including spalling) and structural response under real fire exposure scenarios. In the last few years there has been limited number of studies on the fire behaviour of HSC. Most of these studies focused on either material response—on small scale HSC cylinders tests, or on structural response—mainly on HSC columns.

*Corresponding author.
E-mail address: kodur@egr.msu.edu (V.K.R. Kodur).

0379-7112/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.firesaf.2006.10.006

There have been no studies that integrated the material and structural response of HSC. In this paper, based on a detailed literature review, the fire behaviour of HSC is examined from material level to structural level. A discussion on the various factors that influence spalling and fire endurance of HSC members is presented. The effect of various factors on fire performance will help in developing solutions for mitigating spalling and enhancing fire endurance of HSC structural members. Such solutions are very critical for updating design standards including ACI 216 [9].

2. Concrete and fire

Structural members are to be designed to satisfy the requirements of serviceability and safety limit states for various environmental conditions. Fire represents one of the most severe conditions and hence the provision of appropriate fire safety measures for structural members is a major safety requirement in building design. The basis for this requirement can be attributed to the fact that, when other measures for containing the fire fail, structural integrity is the last line of defence.

Generally, concrete structural members (traditionally used to be made of NSC) exhibit good performance under fire situations. Studies show, however, that the behaviour of HSC, when exposed to fire scenarios, is different from that of NSC and may not exhibit same level of performance as that of NSC. Further, the spalling of concrete under fire conditions is one of the major concerns due to the low porosity (permeability) in HSC. The spalling of concrete exposed to fire has been observed under laboratory and real fire conditions [2,5,11,13]. Spalling, which results in the rapid loss of concrete during a fire, exposes deeper layers of concrete to fire temperatures, thereby increasing the rate of transmission of heat to the inner layers of the member, including the reinforcement.

It has been proposed that spalling is caused by the build-up of pore pressure during heating. HSC is believed to be more susceptible to this pressure build-up because of its low permeability compared to NSC. The extremely high water vapour pressure, generated during exposure to fire, cannot escape due to the high density of HSC and this pressure often reaches the saturation vapour pressure. At 300 °C, the pressure reaches about 8 MPa. Such internal pressures are often too high to be resisted by the HSC mix having a tensile strength of about 5 MPa [2].

Data from various studies [10,11,14] show that the fire behaviour of HSC, in general, and spalling in particular, is affected by a number of factors. However, in many of the earlier studies, the focus is entirely based either on material characteristics or on structural considerations. In this paper, a holistic approach is used to discuss the effect of various parameters on the fire performance of HSC members.

3. Factors governing fire performance

The fire resistance of a structural member is dependent on the geometry, the materials used in construction, the load intensity and the characteristics of the fire exposure itself. Fire endurance of HSC members depend not only on the extent of spalling but also on the rate of loss of strength in concrete. Further, achieving required fire endurance in HSC member through improved design, rather than through external fire protection, will enhance the cost-effectiveness and aesthetics of the overall structural system.

A review of the literature indicates that the main aim of many researchers was to explore measures for mitigating spalling in HSC [2,4–6,10]. Often, these measures were based on very limited fire tests on small-scale specimens [2,10]. The focus of the current paper is to compile information from previous studies and to evaluate the overall fire endurance of HSC members, which depends not only on the extent of spalling but also on the overall behaviour of HSC member in fire.

Data from various studies carried out in a number of organizations worldwide [3–6,12–14], clearly show that fire performance of HSC, in general, and spalling in particular, is complex and is affected by a number of factors. However, to achieve an optimum design a holistic approach has to be adopted where in the behaviour at both material and structural levels have to be considered. With this approach in mind, and based on the analysis of model predictions, test data, and the visual observations made during and after the fire tests, the factors that influence the fire performance of HSC structural members can be broadly classified into three categories: namely, fire characteristics, material characteristics (including the production process and finishing) and structural characteristics. These factors are briefly discussed below.

3.1. Fire characteristics

The type of fire, the fire size and heat output, has significant influence on the fire performance of a concrete structural system. The high rate of temperature rise can induce spalling in concrete members. This is mainly due to high temperature gradients that develop within a cross section, which in turn increases the pore pressure generated in the concrete. This effect can lead to significant spalling in HSC members. In many of the fire tests, undertaken under hydrocarbon fires, high rate of spalling was observed and this spalling started within the first few minutes of fire exposure [4,5]. This can be explained by the fact that the temperatures attained in the hydrocarbon fire is about 815 °C in the first 3 min of fire exposure, as opposed to about 490 °C in typical ASTM E-119 fire. Thus, higher temperature gradients develop under hydrocarbon fires very quickly once the fire starts.

Much of the current fire provisions contained in codes and standards are based on (standard ASTM-E119 or similar) fire scenarios, which represents typical building fires. These provisions may not be directly applicable to fires resulting in infrastructure projects such as offshore structures, and tunnels due to a wide range of differences in fire characteristics. These fires, often referred to as hydrocarbon fires, typically represented by ASTM-E1529 Standard fire, are much more severe (than building fires) and are characterized by fast heating rates or high fire intensities. In Fig. 1, the time-temperature curves from two standard tests and a typical building fire based on temperature measurements acquired in experiments involving office furnishing conducted by DeCicco et al. [15], are compared. Temperature development in a fire, where hydrocarbons might be present, is likely to be closer to the ASTM E-1529 curve. Thus, the fire in infrastructure projects is likely to be much more intense than typical building fires and can reach very high temperatures within the first few minutes of fire exposure. This will lead to increased thermal stresses and higher probability of spalling. Hence, proper attention should be given to spalling mitigation techniques when HSC structural members are used in applications involving scenarios where a hydrocarbon fire might result.

3.2. Material characteristics

The behaviour of a concrete structural member exposed to fire is dependent, in part, on thermal and mechanical properties of concrete of which the member is composed. Similar to other materials the thermo-physical and mechanical properties of concrete change substantially within the temperature range associated with building fires. These properties vary as a function of temperature and depend on the composition and characteristics of concrete. The strength of concrete has significant influence on the properties of HSC at both room and high temperatures. This variation of properties at elevated temperatures is more pronounced for mechanical properties, which are affected by strength, moisture content, density, heating rate, amount of silica fume and porosity. Based on the review of previous fire resistance studies, the following factors have significant influence on the fire performance of HSC.

3.2.1. Concrete strength

Results from a number of fire resistance tests show that strength of concrete has significant influence on fire performance of concrete members. The higher the strength, or the associated lower permeability, the higher will be the probability of spalling. Further, the loss of strength with temperature is higher for HSC as compared to NSC. A comparison of the variation of strength for HSC and NSC is shown in Fig. 2 as a function of temperature [1]. It can be seen that the rate of loss of strength is higher (and significant) for HSC over the entire temperature range. In addition, the fire-induced spalling of HSC is significantly higher than that for NSC. Based on full-scale fire tests on loaded columns, the spalling performance of NSC columns has been compared with that of HSC columns in a number of studies [11,13]. In majority of these studies, the spalling was quite significant in the HSC columns as compared to NSC columns. While it is hard to specify the exact strength range, based on the available information, concrete strengths higher than 70 MPa are more susceptible to spalling and may result in lower fire resistance.

3.2.2. Silica fume

Results from fire endurance tests on HSC columns [16] clearly indicate that silica fume, and associated concrete strength, has an influence on fire endurance. Based on fire resistance tests, while for NSC columns (concrete strength of about 40 MPa) a fire endurance of about 6 h was obtained [3], for HSC columns (concrete strength of about 114 MPa), with similar confinement, fire endurance of only about 4 h was obtained [11,16]. In these tests, the extent of spalling was very significant in columns with high silica fume content (about 15%). The higher silica fume, and associated compressive strength, increases the extent of spalling, due to increased compactivity, and leads to decreased fire endurance. This could be attributed to the fact that the addition of silica fume appears to reduce the

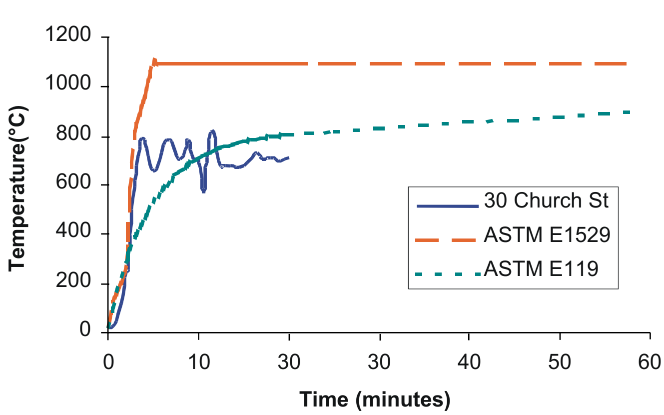

Fig. 1. Time–temperature curves from two standard tests and temperature measurements in a typical building [15].

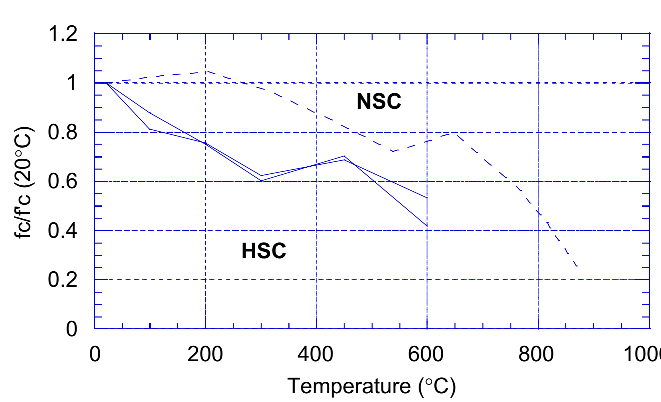

Fig. 2. Variation of strength as a function of temperature for NSC and HSC [1].

permeability of the concrete, restricting the loss of moisture during curing, drying, and the fire test. Further research is needed to quantify the exact extent of silica fume on spalling and fire endurance of HSC members.

3.2.3. Concrete moisture content

The moisture content, expressed in terms of relative humidity (RH), influences the extent of spalling. Higher RH levels lead to greater spalling. Fire-resistance tests on full-scale HSC columns and HSC blocks have shown that significant spalling occurs when the RH is higher than 80% [5,11]. The time required to attain an acceptable RH level (below 75%) in HSC structural members is longer than that required for NSC structural members because of the low permeability of HSC. In some cases, such as in offshore structures, RH levels can remain high throughout the life of the structure and should therefore be accounted for in design [5]. It should be clearly noted that the initial saturation degree is also important, as in the case of RH level, since for dense concrete it takes ages to reach a moisture content in equilibrium with the environment.

3.2.4. Concrete density

The effect of concrete density was studied by means of fire tests on normal-density (made with normal-weight aggregate) and lightweight (made with lightweight aggregate) HSC blocks [5]. The extent of spalling was found to be much greater when lightweight aggregate is used. This is mainly because the lightweight aggregate contains more free moisture, which creates higher vapour pressure under fire exposures. However, it should be noted that the extent of spalling is also dependent on the initial saturation degree.

3.2.5. Fibre reinforcement

Studies show that the addition of polypropylene fibres minimizes spalling in HSC members under fire conditions [4,6,13]. One of the most accepted theories on this is that by melting at a relatively low temperature of 170 °C, the polypropylene fibres create "channels" for the steam pressure within the concrete to escape, thus preventing the small "explosions" that cause spalling. The amount of polypropylene fibres needed to minimize spalling is about 0.1–0.15% (by volume) [4–6,17]. In some studies, addition of steel fibres was found to be beneficial in enhancing fire endurance of HSC column [13]. The presence of steel fibres increases the tensile strength of concrete, at high temperatures, and thus reduces spalling and enhances fire resistance [13,17]. Also, the increased deformation capacity from the addition of steel fibres contributes to minimising spalling.

3.2.6. Type of aggregate

Of the two commonly used aggregates, carbonate aggregate (predominantly limestone) provides higher fire resistance and better spalling resistance in concrete than does siliceous aggregate (predominantly quartz). This is mainly because carbonate aggregate has a substantially higher heat capacity (specific heat), which is beneficial in preventing spalling. This increase in specific heat is likely caused by an endothermic reaction that occurs due to dissociation of the dolomite in the carbonate concrete. Other factors that contribute to enhanced fire resistance properties in carbonate aggregate concrete include strength, ductility, the thermal expansion and the thermal stability. In general the fire endurance of HSC columns made with carbonate aggregate concrete is about 10% higher than HSC columns made with siliceous aggregate concrete [11–13].

3.3. Structural features

The structural behaviour of concrete under fire conditions can be gauged from various fire resistance tests on reinforced concrete (RC) columns. Fig. 3 illustrates the typical structural behaviour of an HSC column as compared to NSC column [3]. In this figure the variation of axial deformation with time is compared for NSC and HSC columns. It can be seen from the figure that the behaviour of the HSC column was different from that of the NSC column and the fire resistance of HSC column to be lower than that of NSC column. There is significant contraction in the NSC column leading to gradual ductile failure. However, in the case of the HSC column the deformation is significantly lower than that of the NSC column and the contraction of the HSC column is much lower. This can be attributed to the fact that HSC becomes brittle at elevated temperatures and the strain attained at any stress level is lower than that attained in NSC for any given temperature [3,11]. Data from previous studies are used to quantify the structural features that contribute to spalling and to the overall fire resistance of HSC members.

3.3.1. Specimen dimensions

A review of the literature shows that the risk of explosive thermal spalling increases with specimen size. This is due to the fact that specimen size is directly related to heat and moisture transport through the structure, as well as the capacity of larger structures to store more energy.

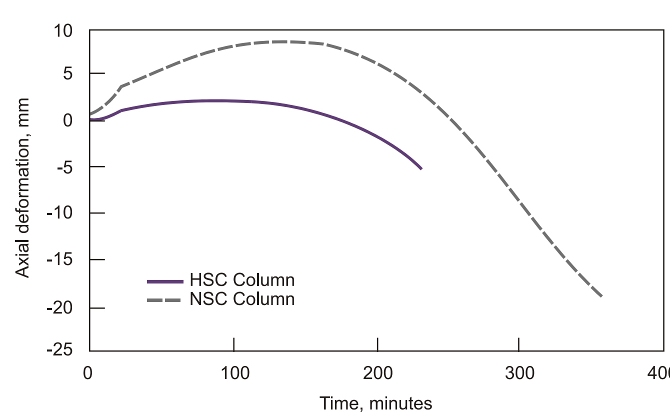

Fig. 3. Axial deformation for HSC and NSC columns [3].

Therefore, careful consideration must be given to the size of specimens when evaluating the spalling problem; fire tests are often conducted on small-scale specimens, which can give misleading results. However, when spalling mitigation measures are incorporated, the risk of explosive spalling decreases and fire resistance increases with the size of the members. Also, similar cover thickness to reinforcement, as in the case for NSC columns, based on structural (corrosion) considerations should be provided for HSC columns.

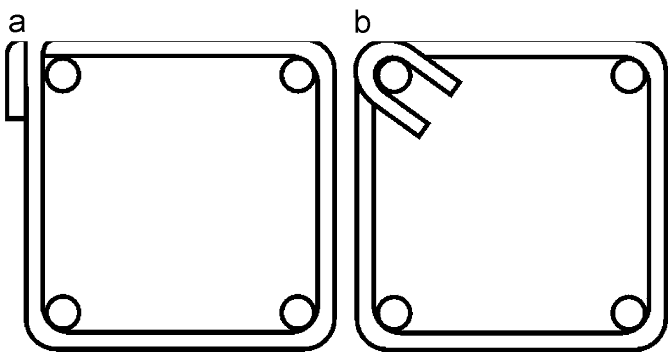

Fig. 4. Conventional and modified tie configuration for reinforced concrete columns [12]: (a) conventional tie configuration; (b) modified tie configuration.

3.3.2. Lateral reinforcement

Results from fire resistance studies clearly show that the layout of ties and confinement of columns have an influence on the fire performance of HSC columns. Higher fire endurance in HSC columns can be achieved by providing improved tie configuration (provision of bent ties at 135° back into the core of the column and increased lateral reinforcement) and with closer tie spacing (at 0.75 times that required for NSC columns). Fig. 4 shows a conventional and modified tie configuration for HSC column. The provision of cross ties also improves fire endurance [11,16]. These improved tie provisions also minimize the extent of spalling in HSC columns. This increased fire endurance and reduced spalling are mainly due to ties holding the longitudinal rebars, firmly in place, under fire exposure conditions. This mechanism helps to minimize the movement and buckling of longitudinal bars which in turn reduces the strains induced in concrete.

Fig. 5 show photographs of the column specimens, with conventional and improved tie configuration, after the fire resistance test as reported by Kodur and McGrath [11]. The extent of spalling in columns, with bent ties configuration, was relatively less compared to that in columns without bent tie configuration. Columns containing only 90° ties would typically lose a significant portion of the columns section upon failure. Columns using 135° ties would exhibit the classic pyramid compression failure

Fig. 5. Comparison of spalling in HSC columns after fire resistance tests [11].

section with the failed section being confined locally to one or two tie spacing.

3.3.3. Degree of restraint

The degree of restraint, during fire exposure conditions, influences the extent of spalling and fire endurance to some extent. The analysis of the test results shows that increasing the degree of restraint increases the generation of forces in the column [14]. However, the forces generated are not very significant when compared to overall column strength. Further, the generated restraint forces in HSC columns were very close to those generated in NSC columns. It should be noted the effect of restraint forces can be significant (may add up to 40%) in the case of beams. However, there is not much test data on this parameter.

3.3.4. Load intensity and type

The type of load and its intensity have significant influence on spalling and the resulting fire resistance. The fire endurance of a RC column increases with a decreasing load. A higher load intensity leads to lower fire resistance, since the loss of strength with a rise in temperature is greater for HSC than for NSC. This has been confirmed through number of fire tests where a loaded HSC structural member was more susceptible to higher spalling than an unloaded member [11–14,16]. This is specially true in columns with conventional tie configuration and subjected to loads greater than service loads. This occurs because a loaded structural member is subjected to stresses due to load in addition to the pore pressure generated by steam. Further, the extent of spalling is higher if the load is of an eccentric (or bending) type since this will induce additional tensile stresses [11].

4. Design implications

High-strength concrete is a high-performing material that offers a number of advantages. In recent years significant research has been undertaken to study the fire behaviour of HSC members and to quantify the factors influencing their spalling and fire endurance. However, to date there are no specific guidelines in codes and standards for the fire resistance design of HSC structural members. Some of the preliminary guidelines present in design standards such as (EN 1992-1-2, Eurocode 2: Part 1.2: design of concrete structures, structural fire design) may need to be fine tuned by including many of the factors discussed above.

As illustrated above, enhancing fire performance of HSC requires proper measures to be considered in the mix-design and in structural design stages. By adopting appropriate measures both at material and structural level, spalling in HSC can be minimized and fire endurance can be enhanced even for concrete strength as high as 110 MPa. While this has been shown through limited fire tests, at present there is no understanding or broad guidelines on the measures needed to address fire problems of HSC. Development of fire resistance design guidelines for HSC members requires detailed numerical modelling studies and quantification of the extent of influence of various factors on spalling and fire resistance. Such models should account for many of the above mentioned factors in tracing the fire performance of HSC members.

5. Summary

HSC is a high-performing material and offers a number of benefits over NSC. However, there is a concern on the occurrence of spalling and lower fire endurance of HSC (as compared to NSC). The fire characteristics, concrete mix properties and structural design features have an influence on the fire performance (both spalling and fire endurance) of HSC columns. The fire intensity, fire size and heat output, and rate of heating influence the degree of spalling and fire endurance duration of HSC members. The main parameters that influence fire performance of HSC at material level are: concrete strength, silica fume, concrete moisture content, concrete density, fibre reinforcement, and type of aggregate. At the structural level, tie spacing, confinement, tie configuration, load levels and size of the members play an important role in determining fire endurance. By adopting proper guidelines, both at material and structural levels, spalling in HSC members can be minimized to a significant extent and fire endurance can be enhanced. Adding polypropylene fibres to concrete mix is much more effective in minimising spalling in HSC under hydrocarbon fires. Similarly, under building fire exposure, using bent tie configuration for lateral reinforcement in HSC columns is very effective in minimizing spalling and enhancing fire endurance.

References

[1] Phan LT. Fire performance of high-strength concrete: a report of the state-of-the-art, National Institute of Standards and Technology, Gaithersburg, MD; p. 1996, 105.

[2] Diederichs U, Jumppanen UM, Schneider U. High temperature properties and spalling behaviour of HSC, In: Proceedings of 4th Weimar workshop on HPC, HAB Weimar, Germany; 1995, p. 219–35.

[3] Kodur VR, Sultan MA. Structural behaviour of high strength concrete columns exposed to fire. In: Proceedings: international symposium on high performance and reactive powder concrete, vol. 4, Sherbrooke, Quebec; 1998. p. 217–32.

[4] Danielsen Ulf. Marine concrete structures exposed to hydrocarbon fires, Report, SINTEF—The Norwegian Fire Research Institute; p. 1997, 56–76.

[5] Bilodeau A, Kodur VR, Hoff GC. Optimization of the type and amount of polypropylene fibres for preventing the spalling of lightweight concrete subjected to hydrocarbon fire, Cem Concr Compos J 2004; 26(2): 163–75.

[6] Hertz KD. Limits of spalling of fire-exposed concrete. Fire Saf J 2003;38:103–16 (National Research Council of Canada National Building Code of Canada Ottawa, ON; 1995).

[7] ACI Committee 318. Building code requirements for reinforced concrete (ACI 318-02), American Concrete Institute, Detroit; 2002.

[8] Canadian Standards Association. Code for the design of concrete structures for buildings. CAN3-A23.3-M02, Rexdale, ON; 2002.

[9] ACI Committee 216. Standard method for determining fire resistance of concrete and masonry construction assemblies, Am Concr Inst, Detroit; 1997.

[10] Phan LT, Carino NJ. Effects of test conditions and mixture proportions on behavior of high-strength concrete exposed to high temperatures. ACI Mater J 2002;99(1):54–66.

[11] Kodur VR, McGrath RC. Fire endurance of high strength concrete columns. Fire Technology—Special Issue 2003;39(1): 73–87.

[12] Kodur VR, Wang TC, Cheng FP. Predicting the fire resistance behaviour of high strength concrete columns. Cem Concr Compos J 2004;26:141–53.

[13] Kodur VKR, Cheng FP, Wang TC. Effect of strength and fiber reinforcement on the fire resistance of high strength concrete columns. ASCE J Struct Eng 2003;129(2):253–9.

[14] Ali FA, Nadjai A, Glackin P, Silcock G. Outcomes of a major research on fire resistance of concrete columns. Fire Saf J 2004;39:433–45.

[15] DeCicco PR, Cresci RJ, Correale WH. Fire tests, analysis and evaluation of stair pressurization and exhaust in high rise office buildings, Brooklyn Polytechnic Institute; 1972.

[16] Kodur VKR, McGrath R. Effect of silica fume and confinement on fire performance of high strength concrete columns. Can J Civ Eng 2006;33:93–102.

[17] Kodur VR. Fiber reinforcement for minimizing spalling in HSC structural members exposed to fire. Innovations in fibre-reinforced concrete for value, ACI Special Publication SP: 216; 2003. p. 221–36.